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XV.

CONTRIBUTIONS FROM THE PHYSICAL LABORATORY OF THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY.

XXXVIII. — ON THE LEAST NUMBER OF VIBRATIONS NECESSARY TO DETERMINE PITCH.

By Charles R. Cross and Margaret E. Maltby.

Presented May 24, 1892.

The present paper is an extension of one by the same authors read at the meeting of this Academy held on June 10, 1891, but not hitherto published. In the investigation described in it a method was employed which was originally proposed by one of the writers a number of years since in a paper read at the Philadelphia Meeting of the American Association for the Advancement of Science, and published in abstract in the Proceedings for 1884, Vol. XXXIII. p. 114.

In that paper attention was called to a defect in the method employed by Savart and Kohlrausch, from which they concluded that at least two complete vibrations are necessary to characterize pitch. This defect is a consequence of the character of the vibrations impressed upon the air by the blows produced by the teeth of the wheel of Savart or the comb of Kohlrausch.

The statement of this difficulty in the paper referred to is as follows: —

"A cardinal defect in these methods of investigating the point in question is that the sound produced by a toothed wheel is very impure; first, because the noise of each separate impulse is mingled with the note produced by the coalescence of the separate impulses; and second, because the proper note, determined by the number of impulses, is itself far from simple in its character. To obtain results that are fully satisfactory the vibrations utilized should be pendular (sinusoidal) in their character. I see no reason in the nature of things why, if a single such simple vibration could be caused to fall upon the ear, it should not produce the sensation of a definite pitch. Rather, under the known action of the separate vibrating parts of the ear, we might suppose that even a small portion of a simple sound-wave, if it produced any recognizable sensation, would give a sound of a pitch corresponding to the length of the complete sound-wave, of which a part had impressed the ear."

The method devised in 1884 to remedy the defect consisted of a telephonic circuit containing two magneto-telephones, connected in the usual manner for the transmission of sound, and a circuit-making wheel. The latter was a wheel of vulcanite, furnished with a single narrow conducting strip of brass extending over a small arc of its circumference. Against the edge of the disk pressed a spring whose end was faced with platinum. If such a wheel is revolved at a uniform speed, it is clear that once in each revolution the circuit between the two telephones is closed for a brief period, whose duration can readily be determined when the speed of the wheel and the angular extent of the conducting sector are known. If now the sound of a tuning-fork giving simple harmonic vibrations actuates the transmitting telephone, the electrical undulation produced will be a sinusoidal one, and the air-waves produced at the receiver will be substantially similar in character, and continuous, provided the contact-making spring rests upon the metal sector of the wheel so as to complete the circuit. But if the wheel is revolved the electrical current is broken, except during a brief interval of time when the spring is in contact with the metallic sector; at which period, however, a current of brief duration is sent through the line and a correspondingly brief sound is produced at the receiver. Except in so far as self-induction and like phenomena act to prevent this, these brief electrical currents are still sinusoidal in character; and hence should give rise at the receiving telephone to waves or portions of a wave of sound which are sinusoidal in form, and should be perceived by the ear as a simple tone. In so far as the motion of the diaphragm of the receiver deviates from a simple harmonic one, either from disturbing electrical effects due to self-induction, or from the acoustic effect of the sudden pull and relaxation which occur when the circuit is made and broken by the contact-making spring, disturbing sounds will of course be added to the simple tone, which would otherwise be the only one produced. But unless the disturbing causes are excessive, the pitch of the simple tone corresponding to that given by the tuning-fork actuating the transmitter will predominate. And as a matter of fact these disturbances are slight, as is shown by the fact that there is no difficulty in transmitting speech through a circuit with a magneto-transmitter at one end and a magneto-receiver at the other, when a rapidly revolving circuit-breaking wheel is interposed to interrupt the current as many as thirty times per second and upwards. At high rates of circuit-breaking the high-pitched note, due to the interruptions, is simply added to the vocal sounds transmitted.

In practice, however, a slight modification of the apparatus described was found to be necessary. As had been surmised when the apparatus was originally devised, clicks and scratches were heard in the receiving telephone when the current was rapidly made and broken by the revolving wheel. These often masked the proper sound of the fork. They seemed to be due to microphonic action at the contact of the spring and brass segment; and although we found that this could often be avoided by careful smoothing of the contact surfaces and proper adjustment of pressure, yet it was difficult to keep the apparatus in good adjustment. For this reason, we substituted for the vulcanite wheel a brass wheel having a single insulating segment of vulcanite. The receiving telephone, whose resistance was 115 ohms, was placed in derivation with the brass wheel, so that during the greater part of the time the receiving telephone was short-circuited and no sensible current passed through it, as the wheel had very slight resistance. But whenever the spring rested on the vulcanite segment the circuit through the wheel was broken; and hence a current passed through the receiving telephone and produced a sound. This arrangement obviated the difficulty just referred to, although care had to be taken to keep the contacts in good condition, as otherwise more or less of a scratching sound was introduced. In order to reduce the resistance of the short circuit through the wheel to a minimum, the current was caused to enter the wheel in the following manner. A disk made of sheet copper was attached to the axle carrying the brass wheel. The edge of the copper disk was amalgamated, and its lower portion dipped into a trough of mercury, thus always securing a good contact. When the current was made to enter the wheel in other ways that were tried, as, for example, through a second spring, it was sometimes found that the resistance of the wheel circuit was not sufficiently low entirely to prevent the production of a sound by the derived current that under these circumstances constantly entered the receiving telephone. With the arrangement described the apparatus worked very satisfactorily, no trace of sound being audible in the receiving telephone except when the spring rested on the vulcanite strip, in which case the pitch of the fork was perfectly clear. A key was inserted so that the sound produced at one or more successive contacts could be caused to enter the ear at will.

In our first experiments we employed as a source of sound a large tuning-fork vibrating in front of a resonator and sounded by a hammer. But we found that this gave too feeble a sound for our purpose. We therefore made use of a small fork, which was set into vibration by a blow, and whose stem was lightly pressed against the disk of the transmitting telephone. A bit of wax placed at the end of the stem was found to be sufficient to prevent any chattering.

The particular form of magneto-telephone which was found most satisfactory as a transmitter, on account of its power, was a bipolar instrument having a large diaphragm, a special form made by the American Bell Telephone Company. For a receiver we found a very sensitive form of magneto-telephone made in Sweden best suited for our purpose.

The tuning-forks employed were of small size, belonging to a Valentine and Carr tonometer. In all of the experiments cited the transmitter was placed in a distant room, so that no sound could possibly reach the ear through the air.

The speed of revolution of the brass wheel was read by a speed-counter, and from this it was easy to determine the period of time during which the contact-spring rested on the vulcanite sector.

The mode of observation adopted consisted in driving the wheel at a rate such that the difference in pitch between the brief sounds heard in the receiving telephone seemed to be distinct. One of the experimenters then sounded the forks successively, presenting them one after another to the telephone, and noting the order in which they were sounded. The listener at the receiver at the other end of the line noted the pitch heard, and these estimations were afterwards compared with the order as noted by the person at the transmitter. The speed was then altered, generally being increased, and a new set of experiments undertaken. In some cases, owing to bad transmission or for other causes, the listener felt uncertain whether the decision noted was correct, and in such cases the result was marked as doubtful.

In the first series of experiments only two notes were compared, which were an octave apart; one, C_3, of 256 vibrations; the other, C_4, of 512 vibrations.

The following figures will illustrate the general character of the results. The line marked "T" indicates the order in which the forks were actually sounded. The line "R" indicates the sound as noted by the listener at the receiving telephone. The number of complete vibrations of the lower note transmitted was 0.88; of the higher, 1.76. The doubtful estimations are followed by an interrogation mark.

TABLE I.

T.	C_3	C_3	C_4	C_3	C_3	C_3	C_4	C_3	C_3	C_4	C_4	C_4
R.	C_3	C_4	C_4	C_3	C_3	C_4	C_4	C_3	C_3	C_4	C_4	C_3

TABLE II.

T.	C_3	C_4	C_3	C_3	C_3	C_4	C_4	C_4	C_3	C_4	C_4	C_4
R.	C_3	C_4	C_4?	C_3	C_3	C_4	C_4	C_3?	C_3	C_4	C_4	C_3

In the first of the above series it will be seen that three estimations were wrong, nine right, none doubtful; that is, 25 per cent were wrong, 75 per cent right. In the second series one estimate was wrong, two were doubtful, and nine correct; that is, 8.3 per cent were wrong, 16.7 per cent doubtful, and 75 per cent correct.

The following tables give a synopsis of results reached with the C_3 and C_4 forks. Except in a very few cases, twelve successive sounds were transmitted. The calculated duration of the sound is in all cases given in terms of the vibration period of both notes. The percentages are given to the nearest whole number. The first column contains the serial number of the experiment; the second (I), the percentage of incorrect estimates; the third (C), the percentage of correct estimates; the fourth (D), the percentage of doubtful estimates; the fifth (L) and the sixth (H), the duration of the sound in terms of the period of the lower and higher notes respectively. The rates are always expressed in complete vibrations.

TABLE III.

Forks C_3 (256 v.), C_4 (512 v.).

No.	I.	C.	D.	L.	H.
1	33	50	17	0.88	1.76
2	25	75	0	"	"
3	8	92	0	"	"
4	8	75	17	"	"
5	0	100	0	"	"
6	0	100	0	"	"
7	0	100	0	0.80	1.60
8	8	92	0	"	"
9	0	100	0	0.73	1.46
10	0	100	0	"	"
11	17	75	8	0.52	1.04
12	42	58	0	"	"
13	27	64	9	0.42	0.84
14	50	42	8	"	"
15	33	67	0	"	"

The following results were obtained with intervals other than the octave.

TABLE IV.

Forks C_3 (256 v.), G_3 (384 v.).

No.	I.	C.	D.	L.	H.
16	25	75	0	0.73	1.10
17	17	83	0	"	"
18	9	83	8	"	"
19	0	100	0	"	"
20	17	75	8	0.41	0.62
21	25	67	8	"	"

TABLE V.

Forks C_3 (256 v.), E_3 (320 v.).

No.	I.	C.	D.	L.	H.
22	33	50	17	0.40	0.50
23	42	58	0	"	"

In the sets of experiments Nos. 22, 23, the contact-spring failed to give even pressure; and it was noticed that the sound was very badly transmitted at certain times, which corresponded with those at which some of the erroneous estimates were made.

TABLE VI.

Forks C_3 (256 v.), C_3 (260 v.).

No.	I.	C.	D.	L.	H.
24	58	25	17	0.40	0.41
25	25	75	0	"	"

It appears from the results given in the preceding tables that even with as small a fraction as $\frac{42}{100}$ of a vibration of the lower fork and $\frac{84}{100}$ of a vibration of the higher fork, when these had an interval of an octave, it was possible to distinguish one note from the other; and when the duration of the tone was greater, but still much less than two complete vibrations of the higher note, the distinction became easy. Nor was the distinction possible merely because of the possession of a clearly defined pitch by the higher note alone, whose period was shorter, so that a greater number of vibrations entered the ear in the time during which the circuit was completed through the telephone; which, it might be surmised, would enable one to distinguish it from the lower note even in the absence of any clearly defined pitch for this latter. On the contrary, the ear always recognized the existence of a distinct pitch with each note, even with the shortest duration of tone which was employed in the experiments; but, as would be expected, the ability to determine with certainty which of the two notes heard successively was the higher in pitch diminished as the duration of the sound diminished, and also as the interval between the two notes became less. The results given in No. 24, Table VI., are curious, and at the time they were reached seemed to be due to a misjudgment as to which of the tones was the higher at the beginning of the experiment. Series No. 25 was made immediately afterwards; but the notes of the forks were carefully listened to separately, in order, if possible, to fix the pitch of each in the mind. As a result three fourths of the estimates were correct.

In another series of observations several forks were struck irregularly, and an attempt was made to state which fork of the set used was heard. The listener knew what were the forks composing the set.

With forks C_3, E_3, G_3, C_4, the results given in Table VII. were reached. The separate series of observations are separated by horizontal lines. The table gives the name and rate of the forks used in the first two columns. In column V is given the number of complete vibrations of each fork in the time during which the sound lasted in the particular experiment referred to; in column O, the number of times each fork was sounded; and in column P, the percentage of correct estimations.

TABLE VII.

Note.	Rate.	V.	O.	P.
C_3	256	2.4	8	100
E_3	320	3.0	13	85
G_3	384	3.6	11	73
C_4	512	4.8	6	83
C_3	256	1.3	9	77
E_3	320	1.6	14	64
G_3	384	2.0	16	69
C_4	512	2.6	7	71
C_3	256	1.2	10	80
E_3	320	1.5	16	62
G_3	384	1.8	15	80
C_4	512	2.4	9	77
C_3	256	1.0	22	64
E_3	320	1.3	21	57
G_3	384	1.5	22	84
C_4	512	2.0	11	82
C_3	256	1.0	14	62
E_3	320	1.3	37	57
G_3	384	1.5	18	88
C_4	512	2.0	8	87
C_3	256	0.9	28	68
E_3	320	1.1	36	64
G_3	384	1.4	27	63
C_4	512	1.8	9	100
C_3	256	0.9	25	72
E_3	320	1.1	34	65
G_3	384	1.4	31	71
C_4	512	1.8	14	85

Table VIII. contains the results of similar observations made upon various series of notes.

TABLE VIII.

Note.	Rate.	V.	O.	P.
C_3	256	1.8	21	62
D_3	288	2.0	14	57
E_3	320	2.3	22	73
F_3—	340	2.4	24	71
G_3	384	2.7	22	64
A_3—	424	3.0	20	80
C_3	256	0.4	30	73
D_3	288	0.5	28	78
E_3	320	0.5	18	83
G_3	384	0.6	21	76
C_3	256	0.4	24	54
D_3	288	0.5	18	66
E_3	320	0.5	23	52
C_3	256	0.4	27	81
D_3	288	0.5	31	68
C_3	256	0.3	48	85
D_3	288	0.3	58	72
C_3	256	0.25	42	81
D_3	288	0.28	40	72

With the exception of the last three comparisons, which are inserted in this place because they were made in immediate connection with the preceding ones in the same table, the experiments whose results are given in Tables VII. and VIII. involve a more serious difficulty in estimation than do those previously considered; since, instead of having to decide merely which of two notes is the higher, it is necessary to determine the musical relation of the various notes in the set sounded. Nevertheless, even with the shortest observed duration of the sound, the uniform preponderance of correct over incorrect or doubtful judgments is altogether too great to be the result of chance.

Moreover, even when the ability to determine which was the higher of two notes was lost, with briefer durations of the sound than those recorded in the tables, there was always a clear difference in the pitch of the two notes; that is, they did not seem like the same sound.

It will of course be observed that, with the method used by us, the element of memory enters, since the pitch of each sound must be carried in the mind. With a direct comparison of the sound heard through the telephone line with that given by a tuning-fork sounded by the observer at the receiving end, it is probable that a still larger percentage of results would be correct. This remains, however, to be actually proved by experiment.

It will also be noticed from the tables that in some cases it seems easier to judge correctly when the two tones make a small interval with each other than when they make a greater one. For example, see the comparisons of C_3 and D_3 in Table VIII. That this is true when the greater interval is an octave might well be expected from the well known liability to confuse notes of this interval; but it is true of notes of other intervals which are not likely to be mistaken for each other.

It is our intention to extend these observations to briefer and longer durations of the sound, and to ascertain what number of vibrations is necessary to recognize the different musical intervals when these are entirely unknown beforehand. To obtain louder sounds it may be possible to use a microphone, although we have avoided this because of the great liability to disturbance of such a transmitter when strong vibrations actuate it. It has also occurred to us that we may use a sinusoidal electrical wave, generated by a peculiar form of alternating dynamo machine, especially devised for the production of such a current by Mr. F. A. Laws, of the Rogers Laboratory. This will give a very loud and at the same time very pure tone. We also intend to study the comparative accuracy of estimation when each sound is heard only once, as in the observations detailed in this paper, with that which is obtained when the sound is repeated two or more times.

The question may be raised, regarding the method employed by us, whether the sound given out by the diaphragm was really of as brief duration as we have assumed it to be. It might be questioned whether the vibration of the diaphragm was not in fact prolonged; so that while the duration of the electric current was, for example, considerably less than the time occupied by two complete vibrations, yet more than two complete sound-waves were actually produced.

Of course, the instant the diaphragm ceases to be actuated by the electro-magnet of the receiving telephone, it will begin to assume its natural rate of free vibration; but how minute a fraction of a second will elapse before it ceases to move at substantially the rate impressed upon it might seem doubtful. But under the circumstances of many of our experiments, in which the duration of the current was from less than one half of a vibration up to one vibration, it certainly is not possible that the vibration should continue without entire change of rate and form for from four to eight times the duration of the forced vibration, which would have to be the case in order to have two complete sound-waves produced.

Furthermore, the damping effect of the magnet upon a telephone diaphragm is such as to prevent more than a very slight amount of persistence of vibration of any kind whatever. This is shown by the facts that the natural note of the diaphragm of a magneto-receiver is never perceived in the ordinary use of the instrument, and that the quality of the sound heard at the receiver is substantially the same, although wide variations may be made in the dimensions of its diaphragm. And if the after-tone of the diaphragm persisted after each pause sufficiently long to produce a recognizable sound of definite pitch, say for the period of two complete vibrations, this would necessarily be noticeable in the actual operation of the instrument, — an effect which is not observed in practice.

Still further, in none of our experiments was there any note observed which corresponded in pitch to the natural note of the diaphragm, — a note whose pitch was so high that it could not have failed to impress itself upon our attention had it been present to any material extent.

These observations seem to show that with ordinary telephone currents there is no material vibration of the diaphragm of the receiver after the forced vibration has ceased. With a stronger current we might expect a certain continuance of the free vibration. What undoubtedly occurs is, that as soon as the electrical undulations cease to act on the receiver, its diaphragm begins to move at a different rate, passing to its free rate of vibration with great rapidity, and assuming this rate unless sooner brought to rest by acoustic and magnetic damping. This action would probably produce a noise of constant pitch, and distinct from the sound of the transmitting tuning-fork.

But although for these reasons it appears extremely unlikely that the diaphragm could continue to vibrate with its rate substantially unchanged for more than a very minute fraction of a vibration, it nevertheless seemed desirable to ascertain by actual and direct experiment whether this is the case.

For this purpose the following apparatus was devised. A Lissajous comparator, with its vibration maintained electrically, was employed in the usual manner to study the motion of a very minute glass bead mounted upon the diaphragm of a magneto-receiver, through the coils of which was carried an alternating current. The glass bead was illuminated by sunlight or the electric arc. The rate of the fork was 128 complete vibrations per second. The alternating current could be caused to flow through the telephone coils for a definite time by the same circuit-making wheel which was used in the experiments already described. As we desired to use a far stronger current than that produced by the transmitting telephone, we made use of the alternating current from a transformer excited by a Thomson-Houston alternating current machine, making 128 complete alternations per second. The strength of the current through the coils was varied by a set of resistances made of incandescent lamps from a maximum of about 100 milliampères to a minimum of about 50 milliampères, an amount vastly in excess of any telephone current. When the circuit-making wheel was at rest and in the proper position the curves of Lissajous were clearly seen. The motion of the bead was very nearly a simple harmonic one, so that the curves observed were ellipses, passing into the limiting oblique straight lines. Difficulty was met with from variations in the rate of alternation of the current, arising from very slight variations in the speed of the dynamo machine, so that it was necessary to utilize such moments as were found to be available when the steadiness was sufficient. If the circuit-making wheel is in motion, it is clear that the appearance of the curve seen will depend upon the duration of the make, or rather upon the duration of the motion of the telephone diaphragm. If the harmonic motion of the diaphragm persists for a period equal to one complete vibration of the fork of the comparator, — or, more strictly, for a period somewhat longer than this, and depending upon the relative phase of the two vibrations when the current begins to flow through the telephone, — it is evident that the curve should be a complete ellipse; but if the harmonic motion of the diaphragm lasts for a less time, then only a portion of an ellipse can be seen; and this will necessarily be deformed, as the curve must begin and end on the same vertical line; which is, of course, the vertical line given by the illuminated bead, as seen through the microscope of the comparator when no current is passing through the telephone.

The method has not yet been sufficiently perfected to give accurate quantitative results; but with the rate of alternation as stated, viz. 128 per second, and with the strong current used, in some cases over 500 times as great as the ordinary current furnished by a magneto-transmitter, with a calculated duration of current of from $\frac{1}{512}$ of a second to $\frac{1}{256}$ of a second, in no case was a complete ellipse observed. In many cases the duration as determined from the curve appeared to be substantially the same as the calculated amount; and when there was a prolongation of the motion it was evident from the character of the curve that this was due to free vibration of the diaphragm.

From these results it would appear that the method used by us is not open to the objection referred to, and that there is really no material prolongation of the harmonic motion of the diaphragm of the telephone after the electric undulations have ceased to actuate it. Moreover, with the very weak current used in the transmission of the sounds of the tuning-forks in our experiments, any such prolongation, if it existed, would of course be far less than with the strong current used in testing the point immediately under consideration. The effect of an increased rate of alternation ought to be studied, but the damping effect of the magnet would be greater at higher rates.

Some other experiments were made, however, with a current having 256 complete alternations per second, and of a rigorously simple harmonic form; but much difficulty was experienced in securing sufficiently equable driving with such means as were available at the time of the experiment, so that further work in this direction had to be postponed until better conditions for steadiness could be secured.

The improbability of any prolongation of the sound vibrations within the ear itself has been shown by Herroun and Yeo.*

A few experiments were made by us with a view of gaining some information regarding the free vibration of the telephone diaphragm after it was pulled to one side and suddenly released. For this purpose a direct current was substituted for the alternating current used in the experiments already described. The strength of the current was substantially the same as before. When the circuit-making wheel completed the circuit, the diaphragm was suddenly drawn toward the magnet and released quickly, when the circuit was broken. With a duration of current of about $\frac{1}{512}$ of a second the free vibration seemed to last for about the same period. With a duration of current of $\frac{1}{256}$ of a second, the free vibration lasted from $\frac{1}{512}$ of a second to $\frac{1}{256}$ of a second. With a duration of current of $\frac{1}{128}$ of a second, the free vibration often lasted as long as $\frac{1}{128}$ of a second. Under these circumstances the curve frequently showed clearly the character and rate of the free vibration of the diaphragm.

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* Proc. Royal Soc., Vol. L. p. 318.

It is uncertain whether it will be possible to study the duration of the motion of the diaphragm by employing such currents as are ordinarily used in telephony, as the effect of these is so slight. In such a research it may prove advantageous to employ two telephones in circuit, each furnished with a mirror, and giving a fragment of a Lissajous curve when a beam of light is successively reflected from the mirrors, the momentary current being sent through the telephones by the circuit-making wheel; or a telephone with an objective carried by its diaphragm might be substituted for the fork of the comparator.

Two other methods have occurred to us of investigating the subject under consideration, which we hope to be able to make use of. The first of these is to employ the wave siren of Koenig, using a disk possessing only a single undulation of the sinusoid, or a fraction of an undulation; or, for repeated sounds, an ordinary disk with only a definite fractional part of the undulations exposed to the action of the jet of air. Or perhaps the same result may be obtained by the use of a narrower slit than that ordinarily employed, so that the air jet shall cover only a portion of the sinusoid.

The second method is to employ a phonograph, on the wax cylinder of which are impressed sinusoidal undulations produced by the sound of a tuning-fork. If only a single such undulation, or portion of an undulation, is allowed to remain, after removing the others by paring away the wax, the diaphragm will necessarily execute only a single harmonic vibration, or fraction of a vibration, when the cylinder is rotated in the ordinary manner.

Rogers Laboratory of Physics,
May, 1892.